Experimental searches for tHq

TOP 2014, Cannes

Christian Böser[1] on behalf of the ATLAS and CMS collaborations,
prepared with the help of Andrey Loginov[2] | 02.10.2014

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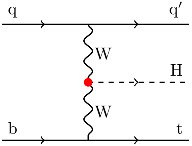
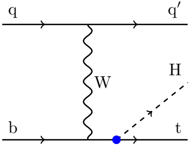
Introduction to pp $\rightarrow$ tHq

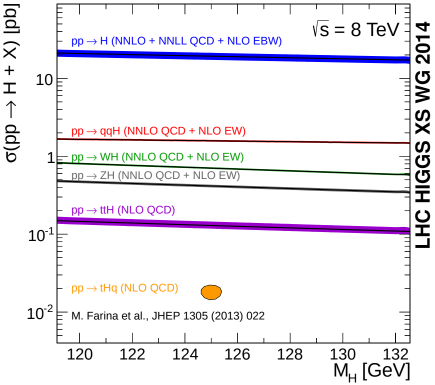
- Investigate coupling of the Higgs boson to fermions $\rightarrow \mathcal{A}_{\text{tHq}} \propto (\kappa_V - \kappa_f)$





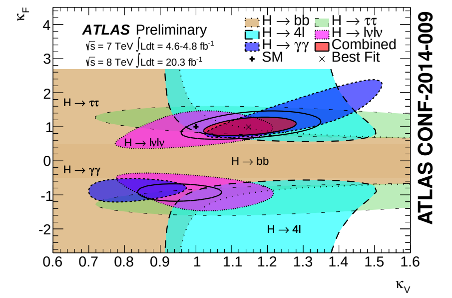
- Destructive interference in SM
  $\Rightarrow$ cross-section is 18.3 fb
- With $\kappa_t^\dagger = -1$
  - $\sigma_{\text{tHq}} = 234$ fb
  - 13 times enhanced compared to SM case
  - BR(H $\rightarrow \gamma\gamma$) 2.4 times enhanced

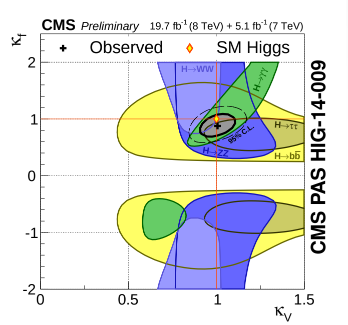
$$^\dagger \ \kappa_t = Y_t / Y_t^{SM}$$



Motivation

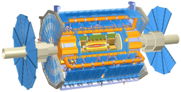
- tHq also sensitive to other modifications of the SM (FCNC, single vector-like quarks, ..)



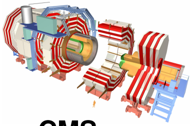


- Coupling constraints from ATLAS + CMS disfavor $\kappa_t = -1$, under assumption of only SM contributions to the total width
- BSM contributions to the loops in the $H\gamma\gamma$ and Hgg couplings are allowed $\rightarrow \kappa_t = -1$ still tolerated

Experimental investigation of tHq and κ_t



ATLAS



CMS

ATLAS		CMS
Constraints on κ_t via $t\bar{t}H$ search	**Approach**	Search for tHq with $\kappa_t = -1$
$H \rightarrow \gamma\gamma$	**Channels**	$H \rightarrow \gamma\gamma$ $H \rightarrow b\bar{b}$
MadGraph + Pythia 8 4-Flavor Scheme (FS)	**tHq MC**	MadGraph + Pythia 6 5FS ($\gamma\gamma$), 4FS (bb)

4-flavor vs. 5-flavor scheme

- Additional b quark only through parton shower in 5-flavor scheme
- Better description of spectator b quark kinematics in 4-flavor scheme

CMS: Direct search for tHq and H $\rightarrow \gamma\gamma$ with $\kappa_{\mathrm{t}} = -1$

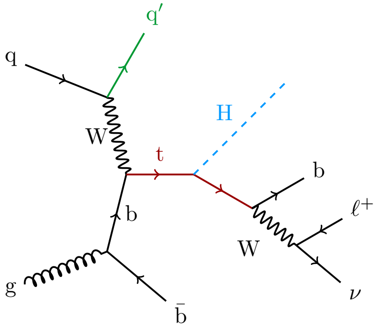
CMS-PAS-HIG-14-001

CMS H $\rightarrow \gamma\gamma$: Overview

- Search for resonance in m($\gamma\gamma$) distribution

Reconstruction

- Higgs: 2 photons with $p_T > 50 \cdot m_{\gamma\gamma}/120$ and 25 GeV
- Top:
  - 1 lepton with $>$ 10 GeV and ΔR $>$ 0.5 w.r.t. photons
  - 1 b-tagged jet with $>$ 20 GeV
  - No cut on $\not{E}_T$
- Recoil jet: Hardest additional jet, must have $p_T > 20$ GeV and $|\eta| > 1$

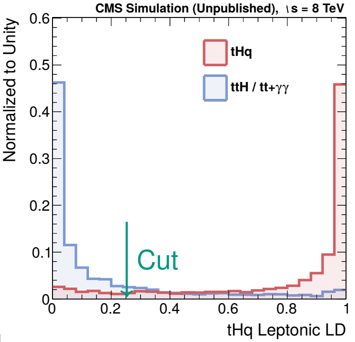


CMS $H \rightarrow \gamma\gamma$: Overview

- Search for resonance in $m(\gamma\gamma)$ distribution

Reconstruction

- Higgs: 2 photons with $p_T > 50 \cdot m_{\gamma\gamma}/120$ and 25 GeV
- Top:
  - 1 lepton with $>$ 10 GeV and $\Delta R > 0.5$ w.r.t. photons
  - 1 b-tagged jet with $>$ 20 GeV
  - No cut on $\not{E}_T$
- Recoil jet: Hardest additional jet, must have $p_T > 20$ GeV and $|\eta| > 1$



Optimized in blind way

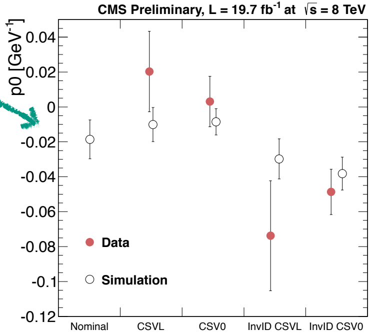
- 5-variable likelihood discriminant (LD) to suppress $t\bar{t}H$ background
- Cut on LD > 0.25
- Ensures $t\bar{t}H$ contamination $< 10\%$
- Selection efficiency tHq: 17%

Process	Yield
tHq ($\kappa_t = -1$)	0.67
$t\bar{t}H$	0.03 + 0.05
VH	0.01 + 0.01
other H	0

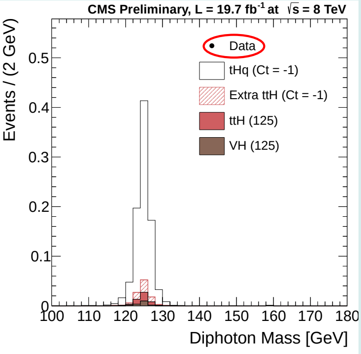
CMS H $\rightarrow \gamma\gamma$: Results

Background shape

- Non-resonant background estimation via fit in loosened $m(\gamma\gamma)$-sideband regions
- $\alpha = \frac{\int_{signal\ \ region} f_{bg}(m_{\gamma\gamma})\mathrm{d}m_{\gamma\gamma}}{\int_{sideband\ \ region} f_{bg}(m_{\gamma\gamma})\mathrm{d}m_{\gamma\gamma}} =$ **7.7%**



Opening the box



Zero events observed

95% C.L. upper limit of
4.1$\times$ expected with $\kappa_{\mathrm{t}} = -1$

CMS: Direct search for tHq and $H \to b\bar{b}$ with $\kappa_t = -1$

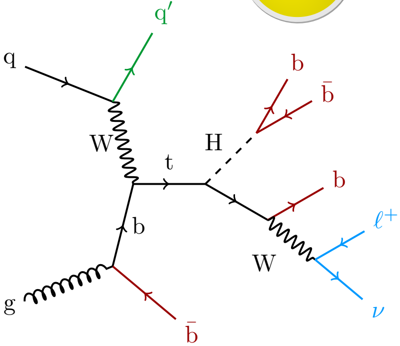
CMS-PAS-HIG-14-015

- Posters @ TOP 2014:
  - *Event interpretation in the context of the search for $H \to b\bar{b}$ in association with single top quarks*, Andrey Popov
  - *Search for $H \to b\bar{b}$ in association with single top quarks as a test of Higgs couplings*, Benedikt Maier

CMS H $\rightarrow$ b$\bar{\text{b}}$: Overview

- Challenging multijet final state
- 3 or 4 b jets (spectator b outside of tracker acceptance in $\sim$ 30% of the cases)
- 1 forward light jet
- 1 isolated charged lepton and $\not\!\!E_T$
- Expected yields

	S/B	
3 tag region	$\sim$ **0.7**%	(13/1900 events)
4 tag region	$\sim$ **2.1**%	(1.4/66 events)



CMS H $\rightarrow b\bar{b}$: Overview

- Challenging multijet final state
- 3 or 4 b jets (spectator b outside of tracker acceptance in $\sim$ 30% of the cases)
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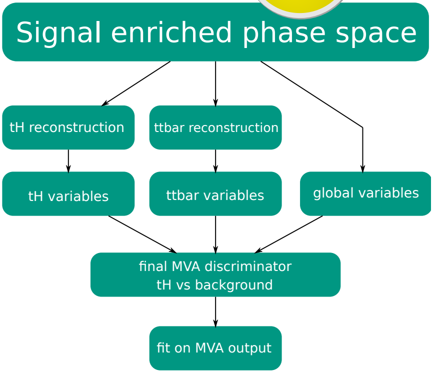
- 1 isolated charged lepton and $\not{E}_T$

- Expected yields

	S/B	
3 tag region	$\sim$ **0.7**%	(13/1900 events)
4 tag region	$\sim$ **2.1**%	(1.4/66 events)

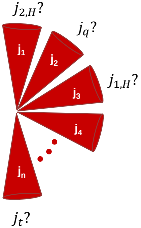
- **$t\bar{t}$ production** dominant background
  - Monte Carlo approach
  - Data-driven cross-check
- Validation of input variables in $t\bar{t}$ control region



- Three MVAs for reconstruction and classification

CMS H → $b\bar{b}$: MVA power[3]

Reconstruction



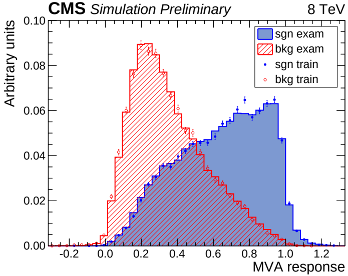
- Jet assignment to final state quarks is combinatorial issue

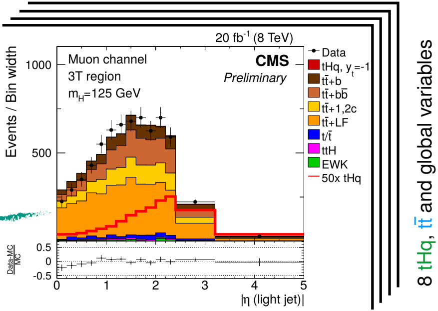
Train two MVAs for jet assignment

- under signal hypothesis
- under $t\bar{t}$ hypothesis

- Reconstruct all possible combinations
- Take assignment with largest MVA output

Classification

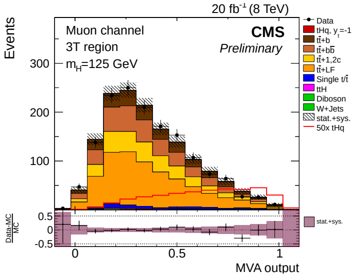




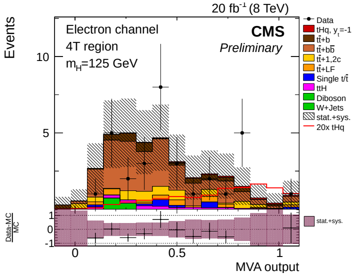
CMS H $\rightarrow b\bar{b}$: Results

Fit on MVA response in 4 regions

3T region (Muon)



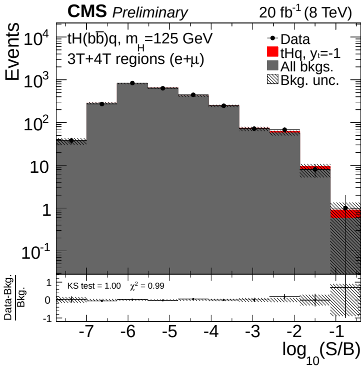
4T region (Electron)



95% Upper Limit on $\sigma/\sigma_{\kappa_t=-1}$

	observed	expected
MC approach	**7.57**	$\mathbf{5.14^{+2.14}_{-1.44}}$
DD cross-check	6.95	$6.24^{+2.26}_{-1.71}$

- Results in good agreement with SM



ATLAS: Constraints on κ_t via $t\bar{t}H$ search

CERN-PH-EP-2014-179

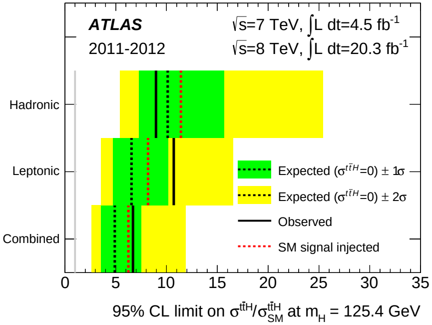
submitted to Physics Letters B NEW

ATLAS H $\rightarrow \gamma\gamma$: Reminder

- Details provided in Mark's talk
- Search for resonance in m($\gamma\gamma$) distribution
- High $t\bar{t}H$ purity event selection

- Selection efficiency tHq: **6.2%**

- tH production non-negligible background



Compared results on $t\bar{t}H$ with H $\rightarrow \gamma\gamma$

	observed	expected (SM signal injected)
ATLAS	**6.7**	**6.2**
CMS	7.4	5.7

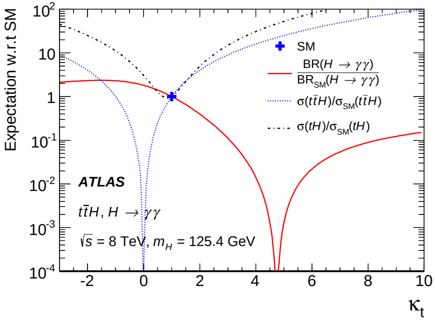
Interpret these results as 95% CL limits on κ_t

ATLAS: From $t\bar{t}H$ search to constraints on κ_t

Yields:

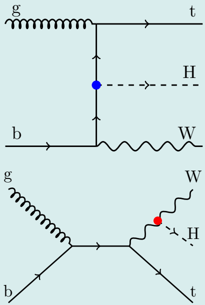
Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	tHq	WtH	N_B
8 TeV leptonic	0.58	1.0%	0.2%	8.1%	2.3%	80.3%	5.6%	2.6%	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic	0.49	7.3%	1.0%	0.7%	1.3%	84.2%	3.4%	2.1%	$2.7^{+0.9}_{-0.7}$

- κ_t changes cross-sections and BR($H \to \gamma\gamma$)



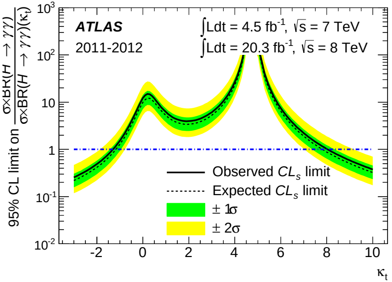
- Accidental cancellations ⇒ minimum of BR($H \to \gamma\gamma$) at $\kappa_t = +4.7$

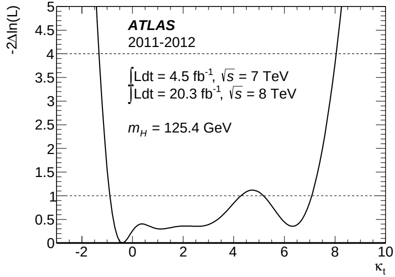
WtH production



aMC@NLO, 5-flavor scheme, interfaced to HERWIG++

ATLAS $H \to \gamma\gamma$: Results





- Scan κ_t, set other couplings to SM values
- Null hypothesis: background + SM Higgs production

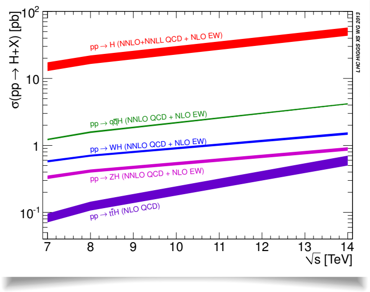
95% C.L. Limit on κ_t

	Observed	Expected
Upper Limit	$+$**8.0**	+7.8
Lower Limit	$-$**1.3**	-1.2

- Consistent with SM expectation of $\kappa_t = 1$
- Best fit for κ_t slightly below 0

Summary

- Investigation of tHq is an active field with a lot of potential
- Great results already with the current data
- Short term plans
  - ATLAS: Including $t\bar{t}H$ results on κ_t into coupling exclusions
  - CMS: Combination of all available tHq searches
- MC: aMC@NLO will replace MadGraph as tHq generator
- Stay tuned!



	$\sigma_{\mathrm{NLO}}(pp) \to tHq$ [fb]	
	$\kappa_F = 1$	$\kappa_F = -1$
8 TeV	18.3	234
14 TeV	88.2	982

BACKUP

Cross sections

- Cross section is challengingly small
  - The main background is $t\bar{t}$; its cross section is provided for comparison

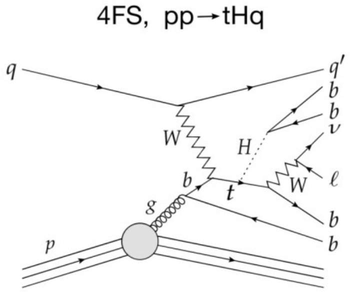
Cross-section	8 TeV	14 TeV
tHq, $y_t = +1$ (SM)	18.3 ± 0.4 fb	$88.2^{+1.7}_{-0.0}$ fb
tHq, $y_t = -1$	$233.8^{+4.6}_{-0.0}$ fb	980^{+30}_{-0} fb
$t\bar{t}$	245^{+9}_{-10} pb	950^{+40}_{-30} pb

tHq cross sections are cited according to M. Farina et al., JHEP 1305 (2013) 022 [arXiv:1211.3736]. Cross-sections for $t\bar{t}$ are calculated in M. Czakon, P. Fiedler, Phys. Rev. Lett. 110 (2013) 252004 [arXiv:1303.6254]. Uncertainties are combined following R. Barlow, arXiv:physics/0306138

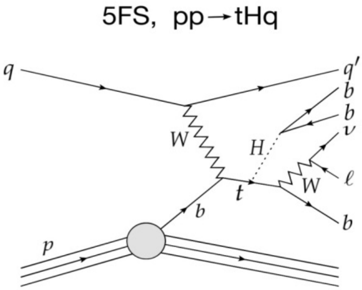
$$\mathcal{A} = \frac{g}{\sqrt{2}}\left[(c_F - c_V)\frac{m_t\sqrt{s}}{m_W v}A\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right) + \left(c_V\frac{2m_W}{v}\frac{s}{t} + (2c_F - c_V)\frac{m_t^2}{m_W v}\right)B\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right)\right]$$

with $c_F \equiv g_{ht\bar{t}}/g_{ht\bar{t}}^{SM}$; $c_V \equiv g_{hWW}/g_{hWW}^{SM}$ (M. Farina et al., arXiv:1211.3736)

Flavor Scheme Comparison



- $m(b) > m(p) \rightarrow$ *b* quark is no proton constituent,
- *b* quarks can only be pair-produced in high $\mathcal{Q}^2$ production



- *b* quarks in initial state, i.e. inside the proton
- Additional *b* comes through parton shower

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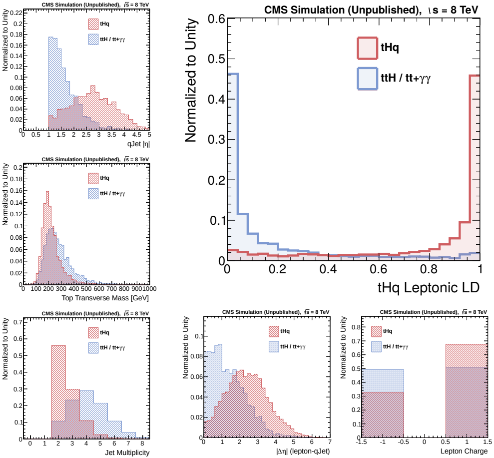
- 5 input variables for likelihood discriminant
  - jet multiplicity
  - transverse mass of the top candidate
  - pseudorapidity of the qJet candidate
  - rapidity gap between the lepton and the qJet
  - charge of the lepton candidate
- Cut on LD > 0.25
- Contribution of $t\bar{t}H$ less than 10%



CMS-PAS-HIG-14-001

$$\alpha = \frac{\int_{signal\ region} f_{bg}(m_{\gamma\gamma})\mathrm{d}m_{\gamma\gamma}}{\int_{sideband\ region} f_{bg}(m_{\gamma\gamma})\mathrm{d}m_{\gamma\gamma}}$$

- Used sidebands for maximum likelihood fit
  - **CSVL:** similar to the nominal selection, but defining the bJet candidate as the hardest jet in the event which pass the 'loose' CSV requirement
  - **CSV0:** same selection as the signal region, but defining the bJet candidate as the hardest jet in the event with $|\eta| < 2.4$, with no b-tagging requirement
  - **InvID CSVL:** same selection as **CSVL**, but with inverted photon ID criteria on one of the two photons
  - **InvID CSV0:** same selection as **CSV0**, but with inverted photon ID criteria on one of the two photons
- Fitted shape of the **CSV0** CR ($\alpha = 7.7\%$) is taken as nominal. Full difference to **InvID CSV0** ($\alpha = 10.2\%$) is taken as a systematic uncertainty (33 %)

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Table : Summary of the adopted systematic uncertainties.

	tHq	$t\bar{t}H$	VH	Continuous BG
Luminosity	$\pm$2.6%	$\pm$2.6%	$\pm$2.6%	-
PDF	+3.1/-2.5 %	$\pm$8%	$\pm$11%	-
QCD Scale	+4.8/-4.3 %	+11/-14 %	$\pm$2.3%	-
Signal Model	$\pm$5.5%	-	-	-
Photon Energy Resolution	+4/-2 %	+4/-2 %	+4/-2 %	-
Photon Energy Scale	+1/-4 %	+1/-4 %	+1/-4 %	-
Photon ID Efficiency	$\pm$2%	$\pm$2%	$\pm$2%	-
Vertex Efficiency	$\pm$0.1%	$\pm$0.1%	$\pm$0.1%	-
HLT	$<$ 0.1%	$<$ 0.1%	$<$ 0.1%	-
JEC	$\pm$1.5%	+3/-5 %	$\pm$8%	-
JER	$\pm$0.5%	$\pm$3%	+8/-0 %	-
b-tagging	$\pm$2%	$\pm$1.5%	$\pm$0.1%	-
PU ID	$\pm$2%	$\pm$0.5%	$\pm$2%	-
Lepton Reconstruction	$\pm$1%	$\pm$1%	$\pm$1%	-
BG shape	-	-	-	33%

CMS-PAS-HIG-14-015

Baseline Selection

- Specialty: variable jet pT threshold
  - $p_T > 20\,\text{GeV}$ for $|\eta| < 2.4$
  - $p_T > 40\,\text{GeV}$ for $2.4 < |\eta| < 4.7$
  - Broad binning in jet η (2.4 – 3.2 & > 3.2) for forward jets

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- Summary of the event selection:

1 μ/e, and it is tight
3-4 jets pass CSVT
$\geqslant$ 1 jet fails CSVT
$p_T(j_4) > 30$ GeV
$\not{E}_T > 35/45\,\text{GeV}$ (μ/e)

- Regions with 3 or 4 b-tags are considered as independent bins in the analysis
- In addition, exploit a $t\bar{t}$ control region. Differences in the selection:
  - Exactly two jets pass CSVT
  - At least three central jets ($|\eta| < 2.4$)

CMS-PAS-HIG-14-015

Input variables for the jet-assignment MVA under the tHq hypothesis

Electric charge of b-quark jet from decay of top quark, multiplied by lepton's charge. The jet charge is defined as in Eq. (1) in Ref. [37], with $\kappa = 1$
ΔR between the two jets from decay of Higgs boson
ΔR between b-quark jet and W boson from decay $\mathrm{t} \to \mathrm{bW}$
ΔR between reconstructed top quark and Higgs boson
Pseudorapidity of recoil jet
Invariant mass of b-quark jet from decay of top quark and charged lepton
Mass of reconstructed Higgs boson
Pseudorapidity of the most forward jet from decay of H
Tranverse momentum of the softest jet from decay of H
Number of b-tagged jets among the two jets from decay of H
Boolean variable that equals 1 if the b-quark jet from decay of t is b-tagged, 0 otherwise
Relative H_T, $(p_\mathrm{T}(\mathrm{t}) + p_\mathrm{T}(\mathrm{H}))/H_\mathrm{T}$

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Input variables for the jet assignment under the $t\bar{t}$ hypothesis. In the descriptions, t_{had} and t_{lep} stand for hadronically and leptonically decaying top quarks, respectively.

Difference of electric charges of b-quark jets from decays of t_{had} and t_{lep}, multiplied by lepton's charge
ΔR between the two light-flavor jets from decay of t_{had}
ΔR between b-quark jet and W boson from decay $t_{had} \rightarrow bW$
ΔR between b-quark jet and W boson from decay $t_{lep} \rightarrow bW$
Difference between masses of t_{had} and W from decay of t_{had}
Pseudorapidity of t_{had}
Invariant mass of b-quark jet from decay of t_{lep} and charged lepton
Mass of W from decay of t_{had}
Number of b-tagged jets among the two light-flavor jets from decay of t_{had}
Boolean variable that equals 1 if the b-quark jet from decay of t_{had} is b-tagged, 0 otherwise
Boolean variable that equals 1 if the b-quark jet from decay of t_{lep} is b-tagged, 0 otherwise
Transverse momentum of t_{had}
Transverse momentum of t_{lep}
Relative H_T, $(p_T(t_{had}) + p_T(t_{lep}))/H_T$
Sum of electric charges of the two light-flavor jets from decay of t_{had}, multiplied by lepton's charge

CMS-PAS-HIG-14-015

Input variables for the classification MVA. The variables are split into three groups: global variables, variables of the jet assignment under the tHq hypotheses, variables of the jet assignment under the $t\bar{t}$ hypothesis. In the descriptions, t_{had} stands for a hadronically decaying top quark.

Electric charge of the lepton
Pseudorapidity of the recoil jet
Number of b-tagged jets among the two jets from the Higgs boson decay
Transverse momentum of the Higgs boson
Transverse momentum of the recoil jet
ΔR between the two light-flavor jets from the decay of t_{had}
Mass of t_{had}
Number of b-tagged jets among the two light-flavor jets from the decay of t_{had}

CMS-PAS-HIG-14-015

Improvement when omitting single systematic uncertainties on the final combined limit with the MC-based approach and impact of adding single systematic uncertainties on the limit without any systematics. Values denoted with < 1 have a negligible impact compared to the significant figures listed in the table.

Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	17	3
JER	shape	< 1	< 1
BTag light flavor	shape	13	< 1
BTag heavy flavor	shape	17	< 1
Pile up	normalization	< 1	< 1
Unclustered energy	shape	3	1
Lepton efficiency	normalization	5	< 1
Luminosity	normalization	10	< 1
Cross section (PDF)	normalization	8	< 1
Cross section (Scale)	normalization	9	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
Q^2 scale ($tHq + t\bar{t}$)	shape	20	4
Matching	shape	2	2
Top p_T reweighting	shape	19	2
$t\bar{t}$ HF rates (b)	normalization	13	< 1
$t\bar{t}$ HF rates ($b\bar{b}$)	normalization	15	< 1
$t\bar{t}$ HF rates (c / $c\bar{c}$)	normalization	13	1

CMS-PAS-HIG-14-015

Improvement when omitting single systematic uncertainties on the final combined limit for the data-driven approach and impact of adding single systematic uncertainties on the limit without any systematics. Values denoted with ¡ 1 have a negligible impact compared to the significant figures listed in the table. The BTag systematic is divided into its effect on the data-driven tt sample (dd-tt) and the other backgrounds (MC), which are taken from MC.

Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	< 1	< 1
JER	shape	< 1	< 1
BTag light flavor (MC)	shape	< 1	< 1
BTag heavy flavor (MC)	shape	6	3
Pile up	normalization	< 1	< 1
Unclustered energy	shape	< 1	< 1
Lepton efficiency	normalization	< 1	< 1
Luminosity	normalization	< 1	< 1
Cross section (PDF)	normalization	< 1	< 1
Cross section (Scale)	normalization	< 1	< 1
Q^2 scale (tHq)	shape	< 1	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
BTag light flavor (DD $t\bar{t}$)	shape	4	< 1
BTag heavy flavor (DD $t\bar{t}$)	shape	< 1	< 1
$t\bar{t}$ contamination	shape	9	16
Method bias	shape	9	3
Scale	shape	< 1	< 1
$t\bar{t}$ HF rates (b)	shape	12	3
$t\bar{t}$ HF rates ($b\bar{b}$)	shape	15	5
$t\bar{t}$ HF rates (c / $c\bar{c}$)	shape	< 1	< 1

ATLAS CONF-2014-043

Run I: Object and Event Selection

- Trigger / Objects
  - EF_g35_loose_g25_loose, p_T^{γ} >0.25/0.35*$m_{\gamma\gamma}$ GeV
  - p_T^e > 15 GeV(*medium++*), p_T^{μ} > 10 GeV(*staco*), p_T^j > 25 GeV
  - |JVF|> 0.5, btag@80% (continuous MV1c)
- Hadronic:
  - $N_{jet} \geq 6$ @ 25 GeV, $N_{btag@80\%} \geq 2$, $N_{lep} = 0$
  - $N_{jet} \geq 5$ @ 30 GeV, $N_{btag@70\%} \geq 2$, $N_{lep} = 0$
  - $N_{jet} \geq 6$, $N_{btag@60\%} \geq 1$, $N_{lep} = 0$
  - Optimization:
    - Suppress non-Higgs processes
    - High purity of ttH w.r.t. non-ttH Higgs processes (ggF)
- Leptonic:
  - $N_{lep} \geq 1$, $M_{e\gamma}$ veto, $N_{btag@80\%} = 1$, MET > 20 GeV
  - $N_{lep} \geq 1$, $M_{e\gamma}$ veto, $N_{btag@80\%} \geq 2$
  - Optimization:
    - High ttH signal efficiency

ATLAS CONF-2014-043

Table : Summary of systematic uncertainties on the final yield of events for 8 TeV data

	$t\bar{t}H$ [%]		tHq [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity					± 2.8			
Photons	± 5.6	± 5.5	± 5.6	± 5.5	± 5.6	± 5.5	± 5.6	± 5.5
Leptons	< 0.1	± 0.7	< 0.1	± 0.6	< 0.1	± 0.6	< 0.1	± 0.7
Jets and E_T^{miss}	± 7.4	± 0.7	± 16	± 1.9	± 11	± 2.1	± 29	± 10
Bkg. modeling	0.24 evt.	0.16 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	$+7, -6$		$+14, -12$		$+14, -12$		$+11, -11$	$+5.5, -5.4$
MC Modeling	± 11	± 3.3	± 12	± 4.4	± 12	± 4.6	± 130	± 100

ATLAS CONF-2014-043

Process	σ [pb] at 7 TeV	σ [pb] at 8 TeV
$t\bar{t}H$	$0.086^{+0.008}_{-0.011}$	$0.129^{+0.012}_{-0.016}$
$tHqb$, $\kappa_t = +1$	$0.0111^{+0.0009}_{-0.0008}$	$0.0172^{+0.0012}_{-0.0011}$
$tHqb$, $\kappa_t = 0$	$0.040^{+0.003}_{-0.003}$	$0.059^{+0.004}_{-0.004}$
$tHqb$, $\kappa_t = -1$	$0.129^{+0.010}_{-0.009}$	$0.197^{+0.014}_{-0.013}$
WtH, $\kappa_t = +1$	$0.0029^{+0.0007}_{-0.0006}$	$0.0047^{+0.0010}_{-0.0009}$
WtH, $\kappa_t = 0$	$0.0043^{+0.0011}_{-0.0008}$	$0.0073^{+0.0017}_{-0.0013}$
WtH, $\kappa_t = -1$	$0.016^{+0.004}_{-0.003}$	$0.027^{+0.006}_{-0.005}$
ggF	15.1 ± 1.6	19.3 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.579 ± 0.016	0.705 ± 0.018
ZH	0.335 ± 0.013	0.415 ± 0.017